Lime stabilization of soil-sludge mixtures for a potential use in oxygen barrier for mine site rehabilitation

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ABSTRACT
Lime treatment of Acid Mine Drainage generates sludge that can be mixed with soils to produce soil-sludge mixtures (SSMs) that can be advantageously used as a component of a cover with capillary barrier effects. Generally, SSMs exhibit high water contents. This paper investigates the impact of lime addition on moisture content, post-compaction dry density and saturated hydraulic conductivity of sand-sludge mixtures (SaSM). In this study, sludge contents of 30% and lime dosages of 0 to 10% were used. The results indicate that the water content decreases as the lime dosage increases. The dry density after compaction increases but remains lower than the optimal density of the untreated SaSM. The saturated hydraulic conductivity of SaSMs containing 2 to 6% lime after 24 hours of cure decreases by 3 orders of magnitude compared to untreated SaSMs.

RÉSUMÉ
Le traitement à la chaux du drainage minier acide génère des boues qui peuvent être mélangées aux sols pour produire des mélanges sol-boues (MSB) pouvant être avantageusement utilisés comme composante d'une couverture avec effets de barrière capillaire. En général, les MSB présentent des teneurs en eau élevées. Cet article étudie l'impact de l'ajout de chaux sur la teneur en eau, la densité sèche après compactage et la conductivité hydraulique saturée de mélanges sable-boues (MSaB). Dans cette étude, des teneurs en boues de 30% et en chaux de 0 à 10% ont été utilisées. Les résultats indiquent que la teneur en eau diminue lorsque le dosage de chaux augmente. La densité sèche après compactage augmente mais reste inférieure à la densité optimale du MSaB non traité. La conductivité hydraulique saturée des MSaB contenant 2 à 6% de chaux après 24 heures de cure diminue de 3 ordres de grandeur par rapport aux MSaB non traités.

1 INTRODUCTION

Acid mine drainage (AMD) is one of the most important environmental issues in the mining industry. Once AMD is produced, a treatment system is required to limit the environmental impacts of this AMD. Active treatment is one of the most used methods. One of the commonly used active treatments of AMD is the neutralization with lime (Brown et al. 2002; Younger et al. 2002; Zinck and Griffith 2013). This type of treatment generates large quantities of sludge that are usually stored in settling ponds.

Sludge generated by the active AMD treatment may maintain an alkaline to neutral pH for decades, if not centuries, due to excess alkalinity induced by residual lime within the sludge (Zinck et al., 1997). This alkalinity imparts chemical stability to the sludge and controls its dissolution and remobilization of metals over time, and as long as the exposure conditions are not acidic. In addition, sludge components such as gypsum, calcite, and ferrihydrite are minerals that are often used as raw materials in the manufacturing of building materials or other products.

Sludge can therefore be a valuable material for specific applications that Rakotonimaro et al. (2017) have done a review of. This includes the use of sludge to remove phosphorus from wastewater (Wei et al., 2008, Sibrell et al., 2009), to sequester carbon dioxide (Zinck, 2005; Zinck and Griffith, 2013), to stabilize arsenic contained in contaminated soils (Ko et al., 2013, 2015, Tsang et al., 2013), to produce building materials and in particular for making cement (Simlin, 1998, Simonyi et al., 1977), bricks (Simonyi et al., 1977, Weng et al., 2003) Sludge can also be used as a component of an oxygen barrier of a cover with capillary barrier effects (CCBE) to prevent acid mine drainage during the restoration of mine sites (Zinck et al., 2010, Bouda et al., 2012, Demers et al., 2015a, b, Mbonimpa et al., 2016, Demers et al., 2017).

Demers et al. (2015b) showed that a mixture of tailing, sludge and 2 wt% cement could be a material that would reduce sulphide oxidation.

Mbonimpa et al. (2016) have shown that a mixture of silt and sludge with a sludge content (mass of wet sludge/mass of wet soil) of 25% has suitable hydrogeotechnical properties to be used as an oxygen barrier for a CCBE. However, these silt and sludge mixtures have very low dry densities compared to the optimal dry density. According to Mbonimpa et al. (2016), one of the challenges of effective use of soil-sludge mixtures (SSMs) is their very high natural water contents. This very high water content limits the amount of sludge in SSMs. In fact, increasing the amount of sludge in the mixtures produces SSMs that are difficult to compact and susceptible to shrinkage and cracking. The reduction of this water content with a natural product would improve the hydrogeotechnical properties of SSMs and increase the amount of sludge to use in soil-sludge mixtures.

The treatment of lime soils is a conventional method generally used to improve the properties of clay materials. Thus the treatment of clay soil with lime makes it possible to improve the water sensitivity of clay material (by reducing its plasticity index) and its compacting properties (LCPC-SETRA, 2000, Bourokba Mrabent et al. 2017). The use of lime also reduces the hydraulic conductivity of clay materials (Locat et al., 1996). The SSM lime amendment could therefore help to reduce the water content of SSMs.

This paper investigates the impact of sand–sludge mixture (SaSM) amendment with lime on the hydrogeotechnical properties (water content, dry density and saturated hydraulic conductivity after compaction). The results obtained are discussed in relation to a potential use of SaSMs as the water retention layer material of a capillary barrier covering for the restoration of problem mine sites.

2 MATERIAL AND METHODS

2.1 Basic characteristics of sands and sludges used

In this study, two types of sludge designated respectively by B1 and B2 and sand were used. These materials were sampled at mining sites located in Abitibi- Témiscaminque (Quebec, Canada). Sludge B1 was sampled in an old inactive settling pond while sludge B2 had just been freshly stored after emptying the existing settling basin.

The relative densities (D_r) are respectively 2.4, 2.6 and 2.8 for sludge B1, sludge B2 and sand. Figure 1 shows the grain-size curves of both sludges and sand. The sludges are essentially characterized by fine particles with percentages passing through the 80 µm sieve greater than 95% while the sand has less than 1% particles smaller than 80 µm.

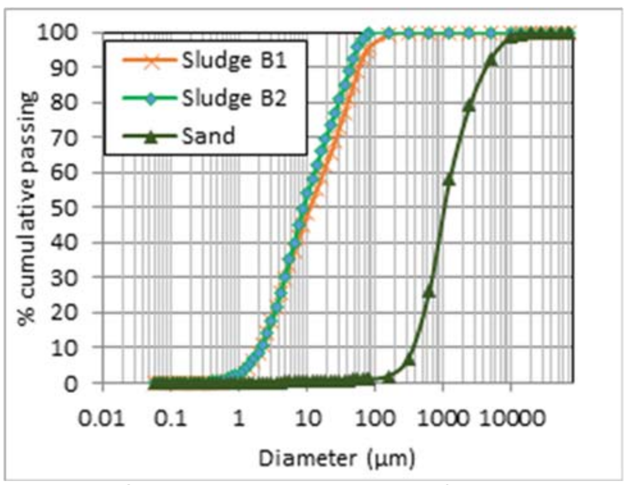

Figure 1. Grain-size distribution curves for the sand and the sludges

The main chemical elements in the sludges and sand are presented in Table 1. The main mineralogical components obtained by XRD for sludge and sand are shown in Figure 2. The sand has a mineralogy composed mainly of quartz (54%) and albite (35%). Sludge B1 consists mainly of gypsum (80%) and sludge B2 is composed mainly of calcite (51%) and corundum (35%).

Table 1. Main chemical elements of the sludges and the sand

Elements (mg/kg)	Sludge B1	Sludge B2	Sand
Al	36470	36130	56670
As	<5	<5	<5
Ba	35	53	235
Be	<5	<5	<5
Bi	<5	<5	<5
Ca	103900	57920	20650
Cd	<5	<5	<5
Co	<5	<5	<5
Cr	29	33	90
Cu	<10	1383	<10
Fe	118800	178900	25740
K	263	689	8330
Li	30	17	28
Mg	15740	23290	10130
Mn	2172	5332	423
Mo	<5	<5	<5
Na	1350	298	22800
Ni	<5	<5	<5
Pb	<5	<5	<5
S	81500	9024	1197
Ti	25	<25	2599
Zn	222	6467	59

1.1 Preparation of the lime-amended sand-sludge mixtures

The preparation of the amended mixtures consisted, first of all, in preparing mixtures of sand and sludge alone before adding any lime. Mixtures with different sludge contents (β; defined as the ratio of wet sludge mass to wet sand mass) were prepared. This study however focuses on presenting the results for the SaSMs at a sludge content of 30% only. Mixtures (with about 500g) of sand and sludge were prepared in the laboratory using a mixer or stand mixer (Figure 3). The initial water content of the sand was 3.5% while the B1 and B2 sludges had initial water contents of 175% and 200%, respectively. Sludge and sand were mixed in the mixer until the mixture became homogeneous. During the preparation of the various batches, the water content (w_m) of the mixture was measured. This initial water content of the mixture can also be estimated from the following equation (Eq.1) (Mbonimpa et al., 2016)

$$w_m = \frac{w_{i-sa}(1+ w_{i-sl})+ \beta\, w_{i-sl}(1+ w_{i-sa})}{1+ w_{i-sl}+\beta(1+ w_{i-sa})} \quad [1]$$

In this equation, $w_{i\text{-}sa}$ and $w_{i\text{-}sl}$ are the initial water contents of sand and sludge, respectively.

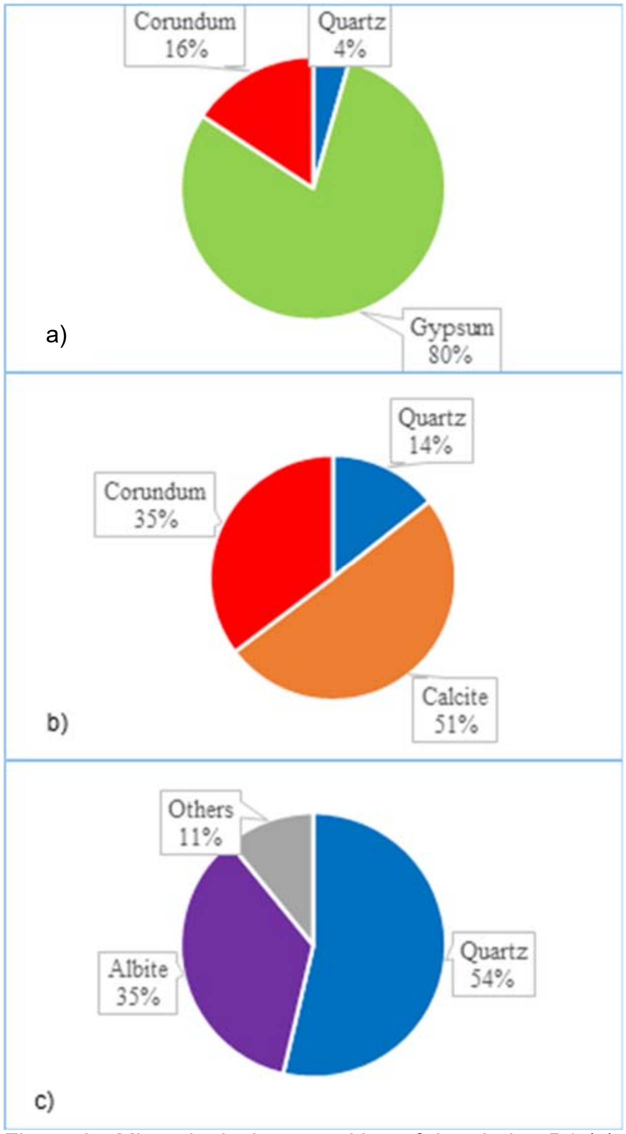

Figure 2. Mineralogical composition of the sludge B1 (a), Sludge B2 (b) and the sand (c)

Once the mixture without lime is homogeneous, different lime was added to the mixture at different dosage (α) (α = mass of lime / wet mass of the mixture) and thoroughly kneaded. In this study, lime dosages (α) ranged from 0 to 10%. Figure 4 shows the different stages of preparation of the lime-amended SaSMs.

Figure 3. Mixer used for the preparation of SaSMs

Figure 4. Preparation of lime-amended SaSM: a) SaSM without lime, b) adding lime to SaSM, c) mixing of the lime-amended SaSM, d) homogeneous lime-amended SaSM at the end of mixing

1.2 Characterisation of non-amended SaSMs

SaSMs alone (without lime) were first characterized to determine their hydrogeotechnical properties (dry density after compaction with the modified Proctor test, saturated hydraulic conductivity). Then, the study of the effect of lime on the hydrogeotechnical properties of the SaSMs was done by assessing the effect of the lime on the water content of the SaSMs, on the dry density and the saturated hydraulic conductivity after compacting the SaSMs to their natural water content.

To study the effect of lime on water content, homogeneized lime-amended SaSM (about 2 500 g) was exposed to the open air under laboratory conditions and weighed regularly over a 48-hour interval, which made it possible to deduce its specific water content. The results of this study will be expressed in terms of water content with respect to lime dosage and time. For this study, lime dosages α of 1, 3, 5, 7 and 10% were studied. It should be mentioned that the exposure of the mixtures to the open air in the laboratory means that finally the combined effect of evaporation and lime on the water content was measured.

To study the compaction properties of lime-modified SaSMs, modified Proctor tests were first performed on non-amended SaSMs in accordance with ASTM D1557-12 to determine the Proctor optimum (maximum dry density ρ_{d-max} and optimal water content w_{opt}). Then, 2, 4, 6, 8 and 10% lime was added to the SaSM, which once homogenized was exposed to evaporation for 24 h, compacted to its current water content following the modified Proctor test procedure. The density of the modified mixture was then compared to the optimal dry density obtained with the Proctor test of the non-amended mixture. The results were also presented in terms of degree of compaction (P_c) as a function of the lime dosage. The degree of compaction is here defined according to the following equation (Eq.2):

$$P_c = \frac{\rho_{d-amended}}{\rho_{d-max}} \text{ x } 100 \qquad [2]$$

Where $\rho_{d\text{-amended}}$ is the dry density obtained after compaction of the amended mixture and $\rho_{d\text{-max}}$ the maximum dry density obtained with the Proctor test of the non-amended mixture.

The saturated hydraulic conductivity was determined with a rigid wall permeameter with variable load according to ASTM D5856-95 (2007a). For sand-sludge mixtures non-amended with lime, the tests were carried out with initial water contents close to the optimal water content obtained with the Proctor test. For lime-amended SaSM, the tests were carried out after 24 hours of curing on the compacted samples as described above. Lime dosages of 2, 4 and 6% were used.

2 RESULTS

2.1 Effect of lime and evaporation on the water content of SaSMs

Figures 5 and 6 show the evolution of the water content according to the lime dosage (Figure 5) and the curing time (Figure 6) for the SaSMs prepared with sludges B1 and B2. In figure 5, it can be observed that the water content decreases regularly with increasing lime dosage. For all curing times, this reduction in water content is more pronounced for lime dosage α below 3% and the reduction rate decreases for α > 3%. For example, for SaSM1, after 24 hours of curing, the water content of the mixture decreased from 22% (initial water content) to 17%, 13% and 12% for dosages of 1, 3 and 5% of lime, respectively.

Figure 6 shows the evolution of the water content with respect to the curing time (0 and 48 hours) for different lime dosages. For all SaSMs, a steeper decrease in moisture content was observed in the first 2 hours compared to subsequent times. For example, for the SaSM prepared with B1 with a lime dosage of 3%, the water content decreases from 22% to 15% between 0 and 2 h and from 15% to 11% between 2 h and 48 h.

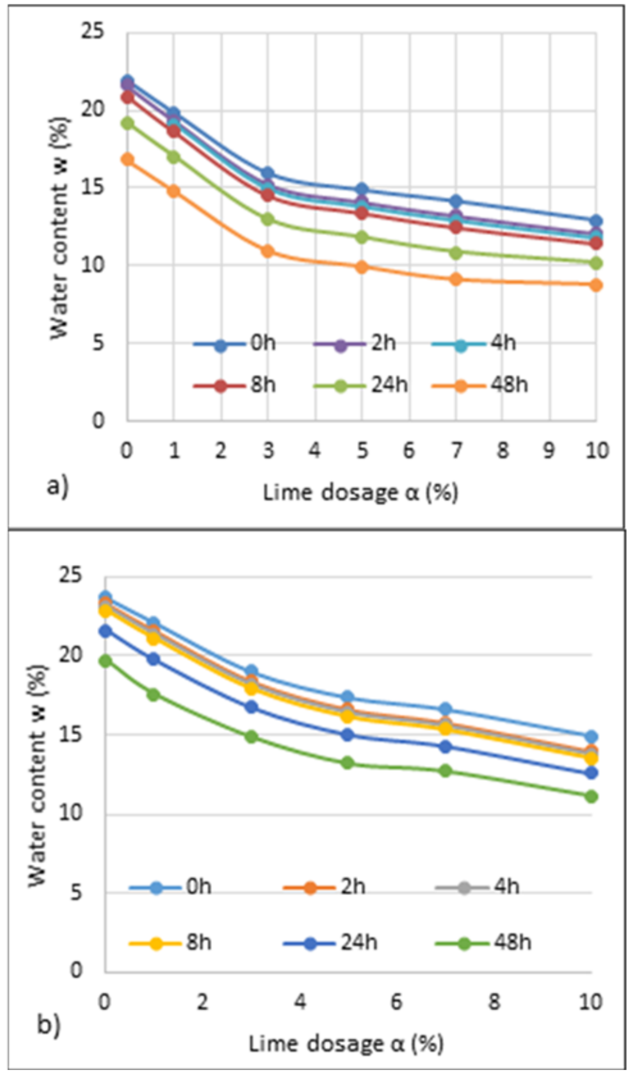

Figure 5. Effect of lime and natural evaporation on the water content of sand-sludge mixtures prepared: a) with sludge B1 and b) with sludge B2

2.2 Lime effect on the compaction properties of SaSMs

Figures 7 and 8 show the impact of lime on the compaction properties of SaSMs. Figure 7 compares the Proctor curve of the non-amended mixtures and the dry density curve of the compacted lime-amended mixtures with respect to the water content, for a given lime dosage and curing time (here 24). It was observed that the water content of the 2500 g was somewhat higher than the water content obtained from samples with 500g (see Figures 5 and 6). According to the Proctor curves of non-amended mixtures, the maximum dry density obtained was 1950 kg/m^3 and 1895 kg/m^3 respectively for SaSMs prepared with sludges B1 and B2, respectively. The corresponding optimal water contents were 11.5% and 13.5%, respectively. Figure 7 indicates that the reduction in the water content of the mixture due to lime and evaporation was accompanied by an increase in the dry density when the lime content varies from 2 to 10%. For example, for the SaSM prepared with B1, the density of the lime-amended mixture increased from 1570 kg/m^3 (for α = 2%) to 1720 kg/m^3 (for α = 10%). The addition of lime improves the compaction characteristics of the mixture which was initially difficult to compact.

Figure 8 expresses the effect of lime on compaction in terms of degree of compaction (P_c) as defined in Equation 2. In this figure, it can be observed that P_c increases with increasing lime dosage. P_c varies from 80% for α = 2% to 88% for α = 10% for the SaSM prepared with sludge B1 and from 83% for α = 2% to 88% for α = 10% for the SaSM prepared with sludge B2.

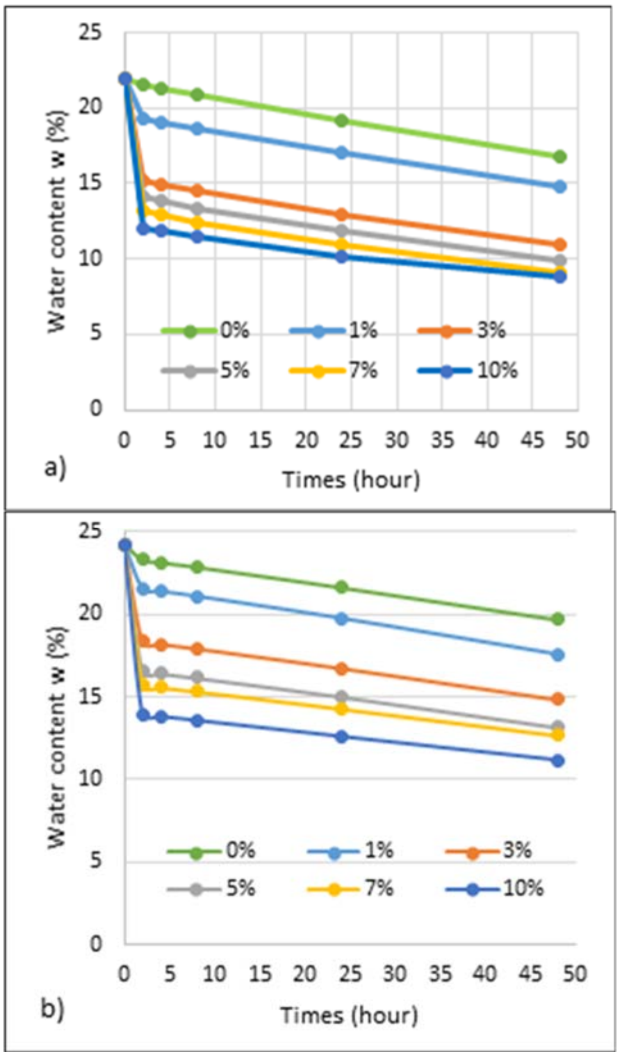

Figure 6. Evolution of the water content of SaSMs under the effect of lime and natural evaporation for different lime dosages: a) SaSM1 prepared with B1 and b) SaSM2 prepared with B2

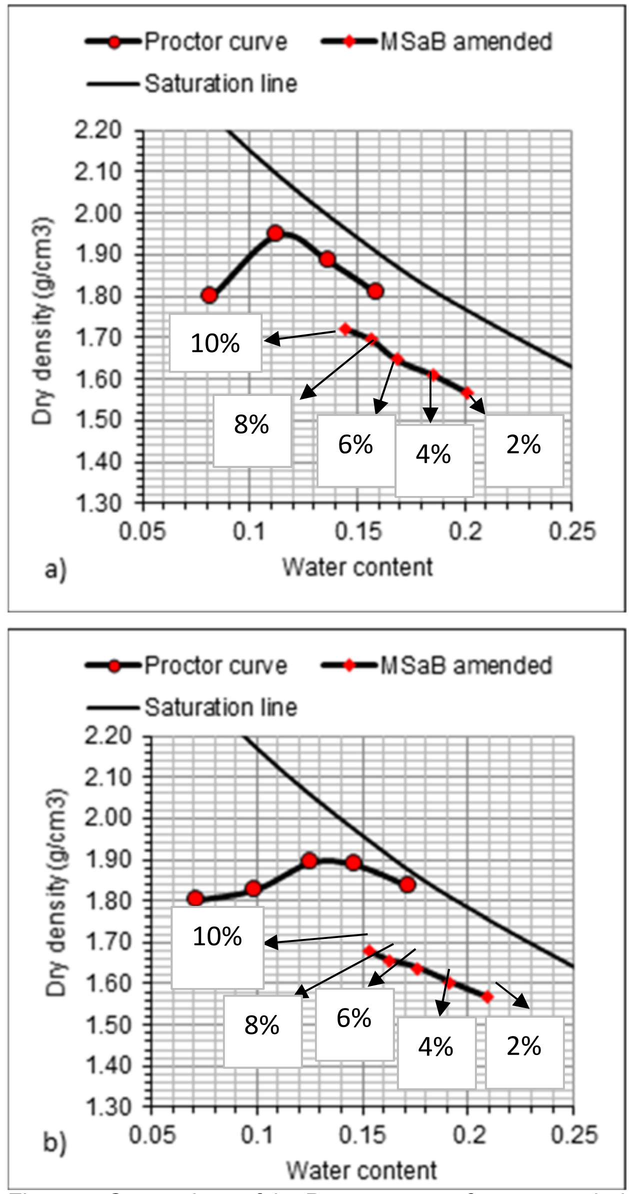

Figure 7. Comparison of the Proctor curve of non-amended SaSM (β = 30%) and compaction curve of lime-amended SaSMs: a) prepared with sludge B1, b) prepared with sludge B2

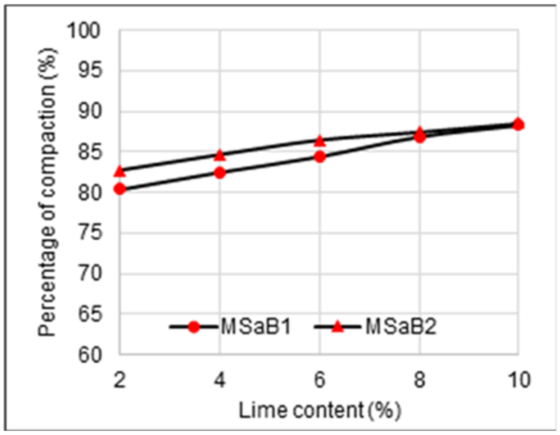

Figure 8. Variation in the of degree of compaction with respect to the lime dosage

2.3 Lime effect on the saturated conductivity

For the saturated hydraulic conductivity (k_{sat}) tests carried out on SaSMs amended with lime, three percentages of lime (α = 2%, 4% and 6%) were used. For α = 0%, 2%, 4% and 6%, the void ratios of the samples were 0.54, 0.59, 0.61 and 0.67 for the SaSMs prepared with sludge B1 and 0.67, 0.82, 0.75, and 0.79 the SaSMs prepared with sludge B2, respectively. Figure 9 shows the variation of k_{sat} as function of the lime dosage for SaSMs prepared with sludges B1 and B2. This figure also shows the saturated hydraulic conductivities of unmodified SaSMs (α = 0%). The results in the figure show that the addition of lime (2%, 4% and 6%) decreases the saturated hydraulic conductivity compared to unmodified SaMs for both B1 and B2 sludges. The results also show that k_{sat} remains in the same order of magnitude (between 10^{-7} and 10^{-6} cm/s) when the lime content was varied from 2 to 6%. The saturated hydraulic conductivity increased from about 10^{-4} cm/s (without lime) to about 10^{-7} cm/s with the addition of lime up to 6%.

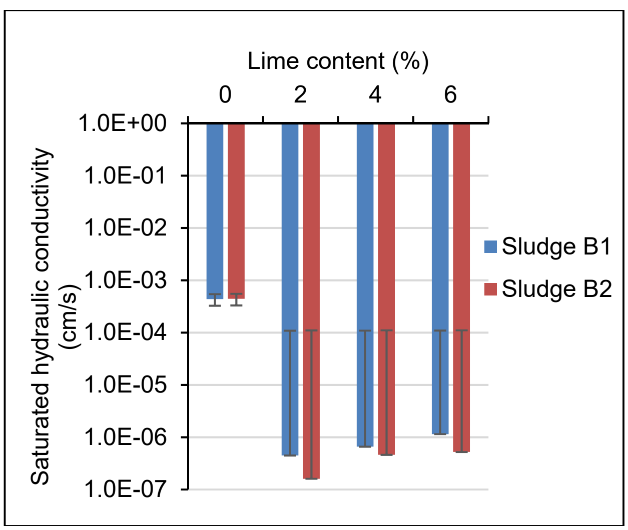

Figure 9. Comparison of the saturated hydraulic conductivity of the non-amended SaSM (β = 30%) and lime-amended SaSMs prepared with sludges B1 and B2

3 DISCUSSION

3.1 Isolation of the effect of the lime alone on the water content of SaSMs

The results presented in Figure 5 on the water contents of the amended SaSMs include the combined effect of lime and evaporation. It would be interesting to isolate the effect of lime alone on the water content of the amended materials. For this, the following approach has been adopted assuming that the evaporation rates of non-amended and amended SaSMs are identical. It was assumed that the water content of non-amended SaSMs subjected to evaporation varies from Δw_{evap} between time t and t + Δt. If w_{am} represents the water content of the amended material under the effect of lime and evaporation at time t + Δt, then the water content of the amended material would have been $w_{am} + \Delta w_{evap}$ in the absence of evaporation. Figure 10 presents the effect of lime alone (different dosages) on the water content of SaSMs prepared with sludge B1 for different curing times. Figure 11 shows the evolution of the water content of the SaSMs for different lime dosages.

According to Figure 6 for a lime dosage α = 0%, the incremental variation of the water content of the non-amended material subjected to evaporation Δw_{evap} varies between 1.4 and 17% for sand-sludge mixtures with B1 for the different curing times considered. Between 2 and 48 h of curing, the corrected water contents of these amended SaSMs appear to increase slightly (Figure 11). This means that the correction of Δw_{evap} is overestimated.

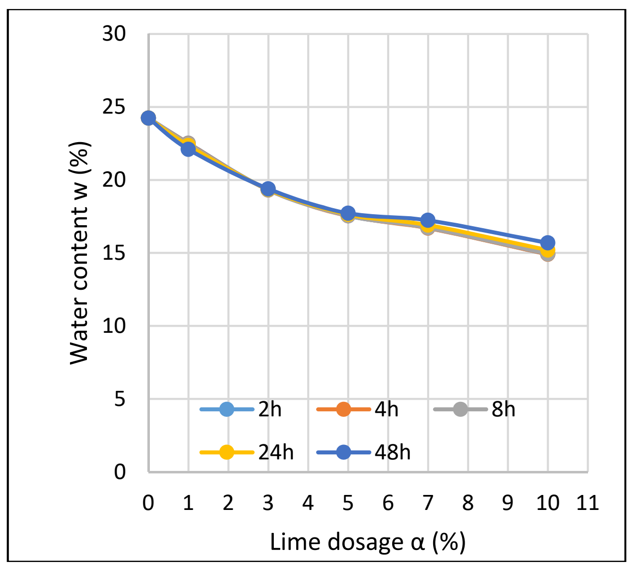

Figure 10. Effect of lime alone on the water content of SaSMs prepared with sludge B1 for different curing times

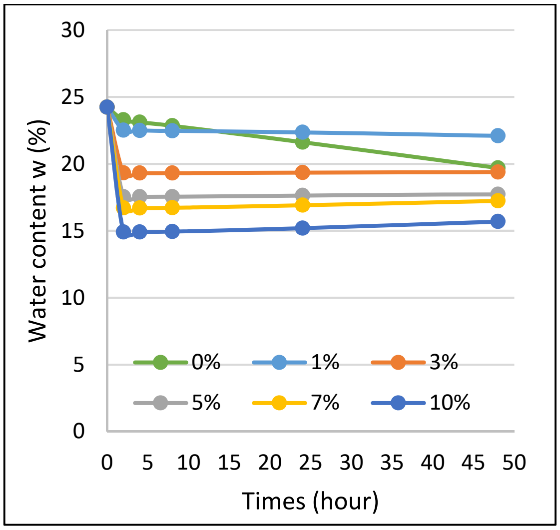

Figure 11. Evolution of the water content of SaSMs prepared with sludge B1 under the isolated effect of lime alone for different lime dosages

3.2 Potential use of SaSMs in CCBE

The results of saturated hydraulic conductivity tests on amended sand-sludge mixtures showed that lime has very beneficial effects. Indeed, while without lime the values k_{sat} were of the order of 10^{-4} cm/s, the saturated hydraulic conductivities of sand-sludge mixtures reached values of the order of 10^{-7} cm/s. These saturated hydraulic conductivity values obtained after lime amendment indicate that these mixtures would be suitable for acting as material for the water retention layer of a CCBE. Indeed, other commonly used material had k_{sat} values < 10^{-5} cm/s (Bussière et al., 2004, Bussière et al., 2007, Dagenais et al., 2012).

Water retention curve (WRC) tests of non-amended sand and sludge mixtures were conducted. Figure 12 shows WRC of the sand alone and of non-amended SaSMs prepared with sludges B1 and B2. The results show the air entry value (AEV) increased from 1.7 kPa for sand alone to 30 kPa and 39 kPa for the mixtures with B1 and B2, respectively. These AEVs are comparable to the values obtained in the literature (AEVs between 20 à 50 kPa) for materials used in water retention layers (Bussière et al., 2004; Bussière et al., 2007; Dagenais et al., 2012).

The effect of lime on the retention capacity of SSMs has not been studied but one can assume that the addition of lime would increase their water retention capacity. Indeed, the addition of lime on silty and clayey materials makes it possible to increase the retention capacity of treated materials compared to untreated materials (Russo, 2005; Tedesco and Russo 2008; Al-Taie et al., 2019).

3.3 Last remarks

This project was limited to studying the effect of lime on moisture content, compaction properties and saturated hydraulic conductivity. SaSM would be suitable as material for the water retention layer of a CCEB only when a suitable material is used in the capillary break layer. Furthermore, the use of SSMs in general and SaSMs will require appropriate long term geochemical and hydrogeochemical properties under field conditions.

It would also be necessary to study the amount of lime that could be added into SSMs knowing that lime, by increasing the pH of the material, can remobilize certain metals such as Fe^{3+}. So lime should be used with care in a practical case.

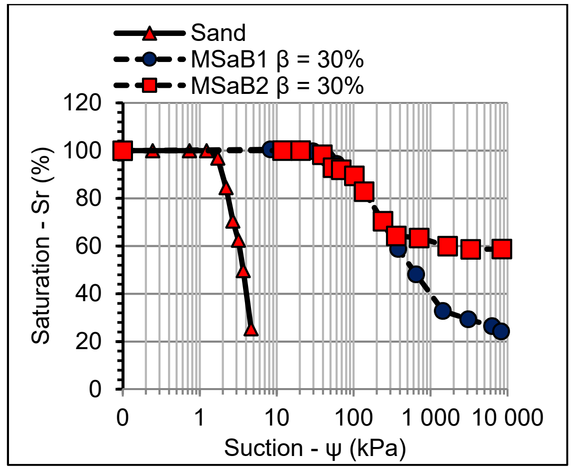

Figure 12. Water retention curve of the sand alone of non-amended SaSMs prepared with sludges B1 and B2

4 CONCLUSION

The results presented in this study show that the addition of lime to sans-sludge mixtures (SaSMs) gives them hydrogeotechnical properties that are very beneficial in the context of mine site restoration. Thus, by reducing the water content of the mixtures, the lime at the same time makes it possible to improve their compaction by increasing the dry density which tends towards the maximum value as the lime dosage is increased. The saturated hydraulic conductivity decreases considerably with the increase in lime dosage and the values obtained after amendment are comparable to those of other materials used in the water retention layer of CCBE. These properties cannot be achieved with non-amended SaSMs.

5 ACKNOWLEDGMENT

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